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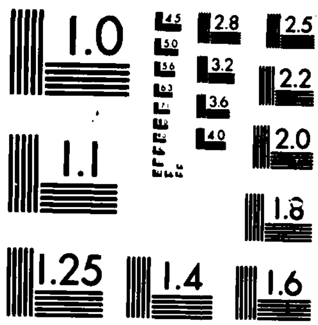


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Structures Technical Memorandum 421

# NUMERICAL COMPLIANCE AND STRESS INTENSITY FACTOR CALIBRATIONS OF MRL COMPACT SPECIMENS

by

M. HELLER and J. PAUL



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# NUMERICAL COMPLIANCE AND STRESS INTENSITY FACTOR CALIBRATIONS OF MRL COMPACT SPECIMENS

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**SUMMARY**

At Materials Research Laboratories (MRL) Melbourne, a compact specimen design has been developed which is suitable for both plane-strain fracture toughness and $J_{IC}$ testing. Compliance and stress intensity factor calibrations are given for the new design of specimen using finite element analyses and the results are compared with those for the ASTM compact specimen.





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CONTENTS

## NOTATION

| | |
|---|---|
| $a$ | Length of crack measured from load line |
| $B$ | Thickness of specimen |
| $\tilde{C}$ | Normalised compliance |
| $E$ | *Young's modulus* |
| $J_{IC}$ | Critical value of J integral |
| $K$ | Stress intensity factor |
| $K_{IC}$ | Plane strain fracture toughness |
| $\tilde{K}$ | Normalised stress intensity factor |
| $P$ | Load applied to specimen at pin hole |
| $r$ | Distance from crack tip |
| $R$ | Radius of pin hole |
| $u$ | Displacement in y direction of node on crack face at distance r behind crack tip |
| $\nu$ | Poisson's ratio |
| $W$ | Width of specimen measured from load line |
| $x,y$ | Cartesian co-ordinate axes system |

## 1. INTRODUCTION

The fracture mechanics parameters $K_{IC}$ (the plane strain fracture toughness) and $J_{IC}$ (the critical value of the J integral) characterise the resistance of a material to cracking for elastic and elastic-plastic conditions at the crack tip respectively. Standard specimen configurations are available for $K_{IC}$ and $J_{IC}$ testing, and these are given in ASTM standards E-399 and E-813 respectively [1,2]. At Materials Research Laboratories (MRL) Melbourne a compact specimen design has been developed which has been found to be suitable for both $K_{IC}$ and $J_{IC}$ testing. For determining $K_{IC}$, a stress intensity factor (K) calibration is required for the specimen, and for determining $J_{IC}$ using the single specimen technique, a compliance calibration is needed. This memorandum describes these calibrations, which were obtained using finite element analyses, and gives equations which have been fitted to the results for convenience.

## 2. ANALYTICAL DETAILS

### 2.1 Specimens and Analysis

The ASTM standard specimen configurations used for $K_{IC}$ testing are shown in Figs. 1 and 2. Two variants of the MRL compact specimen design were investigated and are shown in Figs. 3 and 4. The two specimens are identical except that one has a longer notch than the other. The short-notch specimen is designated as specimen A, and the long-notch specimen is designated as specimen B (the MRL designations are J03 and J43 respectively). Finite element methods were used to determine specimen deformations for two-dimensional conditions. The analyses were carried out for plane stress although plane strain specimen compliances can readily be determined from the plane stress values.

### 2.2 Crack Tip Modelling

Accurate calculations of normalised compliance ($\tilde{C}$) and normalised stress intensity factor ($\bar{K}$) require detailed modelling of crack tip behaviour. A number of finite element methods can be used to model two-dimensional crack-tip behaviour and several of the better ones are reviewed in [3] and [4]. In the present analyses small rectangular iso parametric elements at the crack tip were used with their mid-side nodes shifted to the quarter points [5]. These elements give the required $r^{1/2}$ displacement singularity, they are accurate, and are easy to implement.

## 2.3 Pin Loading

Both specimen geometies were analysed for both point and distributed pin loading. For point loading the load, P, was applied to one node at the top of the hole, and for distributed loading the load was spread evenly across nodes at the top of the hole over a distance equal to the hole radius, R.

## 2.4 Normalised Compliance

Values of normalised compliance were determined using the equation, given in [2], namely

$$\bar{C} = \frac{2EBV}{P} \tag{1}$$

where V is the displacement of the sharp corner on the specimens in the loading direction (see point marked x in Figs. 3 and 4.)

## 2.5 Normalised Stress Intensity Factor

To determine stress intensity factors for the various specimen geometries the equation given in [6] was used, namely

$$K = \frac{uE}{4(1-\nu^2)} \sqrt{\frac{2\Pi}{r}} \tag{2}$$

where u is the y displacement of a near-tip node on the crack face behind the crack tip and r is the distance of that node from the crack tip. Since equation (2) is valid only very close to the crack tip, a corner node (eg node 'Z') of the crack tip element was used in the analyses as indicates schematically in Fig. 5.

Normalised stress intensity factors, $\tilde{K}$, were then obtained using the equation

$$\tilde{K} = \frac{K B \sqrt{w}}{P} \tag{3}$$

where w is the specimen width measured from the load line. This equation is used since, for a compact specimen at a given crack length ratio, $\frac{a}{w}$, K is proportional to $\frac{P}{B\sqrt{w}}$ [7].

## 3. NUMERICAL ANALYSES

Finite element analyses were made with the PAPEC suite of programs on the ARL VAX 11/780 computer. The stiffness matrices were computed using 2 x 2 reduced integration and all solution steps were performed using double precision.

### 3.1 Specimen A

The elastic properties of the material were taken as E = 210 GPa and $\nu$ = 0.3. The specimen thickness was B = 25.5mm and a tensile load of P = 4000N was applied at the pin hole.

Analyses were conducted for values of crack ratio $\frac{a}{w}$ between 0.36 and 0.76, for both point and distributed loading. A typical finite element mesh with point loading is shown in Fig. 6(a) (for $\frac{a}{w}$ = 0.52) and the same mesh with distributed loading is shown in Fig. 6(b). The mesh consists of 154 eight-noded isoparametric quadrilateral elements and 9 six-noded isoparametric triangular elements. As discussed in Section 2.1 the crack tip elements have their mid-side nodes shifted to quarter point positions, and these elements were typically $\frac{1}{25}$ th the length of the crack.

### 3.2 Specimen B

The elastic properties of the material were taken as E = 73 GPa and $\nu = 0.3$. The specimen thickness was B = 6mm and a tensile load of P = 6320N was applied at the pin hole.

Analyses were conducted for values of crack ratio $\frac{a}{w}$ between 0.46 and 0.7, for both point and distributed loading.

A typical finite element mesh with point loading is shown in Fig. 7(a) (for $\frac{a}{w} = 0.52$), and the same mesh with distributed loading is shown in Fig. 7(b). For this specimen the mesh consisted of 212 eight-noded isoparametric quadrilateral elements and 11 six-noded isoparametric triangular elements.

Again the crack tip elements had their mid-side nodes shifted to quarter point positions, and for this specimen these elements were typically $\frac{1}{60}$ th the length of the crack. (The mesh for this specimen was more highly refined than strictly necessary because it was being used for other work involving plasticity analysis).

## 4. RESULTS

Values of normalised compliance ($\bar{C}$) calculated using equation (1) for specimens A and B are given in Tables 1 and 2. For any value of $\frac{a}{w}$ considered the difference in $\bar{C}$ values between specimens or loading is very small and may be neglected when used for test purposes, for example, as can be seen by comparing values at $\frac{a}{w} = 0.56$ or 0.60. A least-squares best fit polynomial equation was determined for the poolled data over the range $0.46 < \frac{a}{w} < 0.7$, with the following result,

$$\bar{C} = b_o + b_1\left(\frac{a}{w}\right) + b_2\left(\frac{a}{w}\right)^2 + b_3\left(\frac{a}{w}\right)^3 + b_4\left(\frac{a}{w}\right)^4 + b_5\left(\frac{a}{w}\right)^5 \qquad (4)$$

where $b_o = -3630.76$
$b_1 = 33917.16$
$b_2 = -125878.0$
$b_3 = 23346.15$
$b_4 = -216373.5$
$b_5 = 80742.64$

Equation (4) is within ± 0.35% of the finite element results for any point within the range noted above.

It should be noted that values of normalised compliance for plane strain conditions can be determined readily from the present results using the equation given in [7]:

$$\tilde{C}_{plane\ strain} = \tilde{C}(1 - \nu^2) \qquad (5)$$

Values of normalised stress intensity factor ($\bar{K}$) calculated using equation (3) for specimens A and B are given in Tables 3 and 4.

For any value of $\frac{a}{w}$ considered the difference in $\bar{K}$ values between specimens or loading is also very small and may be neglected when used for test purposes as, for example, can be seen by comparing values at $\frac{a}{w}$ = 0.56 or 0.60. Again, a least-squares best-fit-polynomial equation was fitted to the poolled results over the range $0.46 < \frac{a}{w} < 0.7$. The derived equation is

$$\bar{K} = \frac{(2 + \frac{a}{w})}{(1 - \frac{a}{w})^{3/2}} \left[ b_o + b_1(\frac{a}{w}) + b_2(\frac{a}{w})^2 + b_3(\frac{a}{w})^3 \right] \qquad (6)$$

where $b_o = 0.21291$
$b_1 = 6.682871$
$b_2 = -12.29665$
$b_3 = 7.320672$

Equation (6) is within 0.35% of the finite element results.

Averaged values of $\bar{C}$ and $\bar{K}$ (determined from finite element analyses) for specimens A and B are compared in Tables 5 and 6 with those for the ASTM compact specimen for selected values of $\frac{a}{w}$. The $\bar{C}$ values for the ASTM specimen were obtained from [2], and the $\bar{K}$ values were evaluated using equation (7.4) given in [7] in conjuction with equation (3) of this memorandum. It can be seen that the MRL specimens have slightly higher values for both $\bar{C}$ and $\bar{K}$ than the ASTM specimens.

Since the values of $\bar{C}$ and $\bar{K}$ determined for both the ASTM and MRL specimens and given in Tables 5 and 6, would be accurate to better than 0.5% the differences in $\bar{C}$ and $\bar{K}$ shown in both Tables 5 and 6 respectively can be attributed to specimen configuration and not to calibration procedure.

## 5. CONCLUSION

Normalised compliance ($\bar{C}$) and normalised stress intensity factor ($\bar{K}$) calibrations for MRL compact specimens A and B have been carried out using finite element analyses.

Polynomial expressions have been fitted to the $\bar{C}$ and $\bar{K}$ calibration results over the range $0.46 < \frac{a}{w} < 0.7$.

The two specimens have essentially the same values for the parameters $\bar{C}$ and $\bar{K}$ over the range of crack lengths considerea even though they have different notch lengths. The MRL specimens however, have higher values for both $\bar{C}$ and $\bar{K}$ than the ASTM compact specimens due to differences in geometry.

## ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Dr R. Jones, Dr G. Clark and Mr T.V. Rose for their helpful discussions and interest shown in this work.

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TABLE 1

**Normalised Compliance Values for MRL Specimen A for Plane Stress Conditions**

| a/w | Normalised compliance | |
|---|---|---|
| | Point pin loading | Distributed pin loading |
| 0.36 | 22.76 | 22.91 |
| 0.40 | 26.62 | 26.77 |
| 0.44 | 31.39 | 31.54 |
| 0.48 | 37.34 | 37.48 |
| 0.52 | 44.74 | 44.88 |
| 0.56 | 54.43 | 54.56 |
| 0.60 | 67.30 | 67.43 |
| 0.64 | 85.00 | 85.12 |
| 0.68 | 109.9 | 110.0 |
| 0.72 | 147.5 | 147.6 |
| 0.76 | 207.3 | 207.3 |

TABLE 2

**Normalised Compliance Value for MRL Specimen B for Plane Stress Conditions**

| a/w | Normalised compliance | |
|---|---|---|
| | Point pin loading | Distributed pin loading |
| 0.46 | 34.49 | 34.63 |
| 0.48529* | 38.46 | 38.60 |
| 0.50882* | 42.35 | 42.92 |
| 0.56 | 54.68 | 54.86 |
| 0.60 | 67.59 | 67.72 |
| 0.66 | 96.71 | 96.82 |
| 0.70 | 127.43 | 127.51 |

* used for additional plasticity analysis

TABLE 3

**Normalised Stress Intensity Factor Values for Specimen A**

| a/w | Normalised stress intensity factor $\tilde{K}$ | |
|---|---|---|
| | Point pin loading | Distributed pin loading |
| 0.36 | 1.445 | 1.445 |
| 0.40 | 1.655 | 1.654 |
| 0.44 | 1.868 | 1.868 |
| 0.48 | 2.115 | 2.114 |
| 0.52 | 2.353 | 2.352 |
| 0.56 | 2.720 | 2.718 |
| 0.60 | 3.188 | 3.188 |
| 0.64 | 3.807 | 3.804 |
| 0.68 | 4.520 | 4.518 |
| 0.72 | 5.677 | 5.674 |
| 0.76 | 7.383 | 7.381 |

TABLE 4

**Normalised Stress Intensity Factor Values for MRL Specimen B**

| a/w | Normalised stress intensity factor $\tilde{K}$ | |
|---|---|---|
| | Point pin loading | Distributed pin loading |
| 0.46 | 1.955 | 1.954 |
| 0.48529 | 2.128 | 2.127 |
| 0.50882 | 2.293 | 2.292 |
| 0.56 | 2.741 | 2.740 |
| 0.60 | 3.195 | 3.194 |
| 0.66 | 4.160 | 4.158 |
| 0.70 | 5.106 | 5.106 |

TABLE 5

**Comparison of Normalised Compliance Values for MRL Compact Specimens and ASTM Compact Specimen**

| a/w | Normalised Compliance $\tilde{C}$ | | Percentage difference |
|---|---|---|---|
| | MRL compact specimens * | ASTM compact specimen | |
| 0.50882 | 42.35 | 39.70 | 6.7 |
| 0.56 | 54.68 | 50.71 | 7.8 |
| 0.60 | 67.59 | 63.50 | 6.4 |
| 0.66 | 96.71 | 92.17 | 4.9 |
| 0.70 | 127.43 | 122.54 | 4.0 |

* Finite element results for specimens A and B averaged.

TABLE 6

**Comparison of Normalised Stress Intensity Factor Values for MRL Compact Specimens and ASTM Compact Specimen**

| a/w | Normalised stress intensity factor $\tilde{K}$ | | Percentage difference |
|---|---|---|---|
| | MRL compact specimens * | ASTM compact specimen | |
| 0.50882 | 2.293 | 2.242 | 2.3 |
| 0.56 | 2.741 | 2.657 | 3.2 |
| 0.60 | 3.195 | 3.084 | 3.6 |
| 0.66 | 4.160 | 3.986 | 4.4 |
| 0.70 | 5.106 | 4.867 | 4.9 |

* Finite element results for specimens A and B averaged.

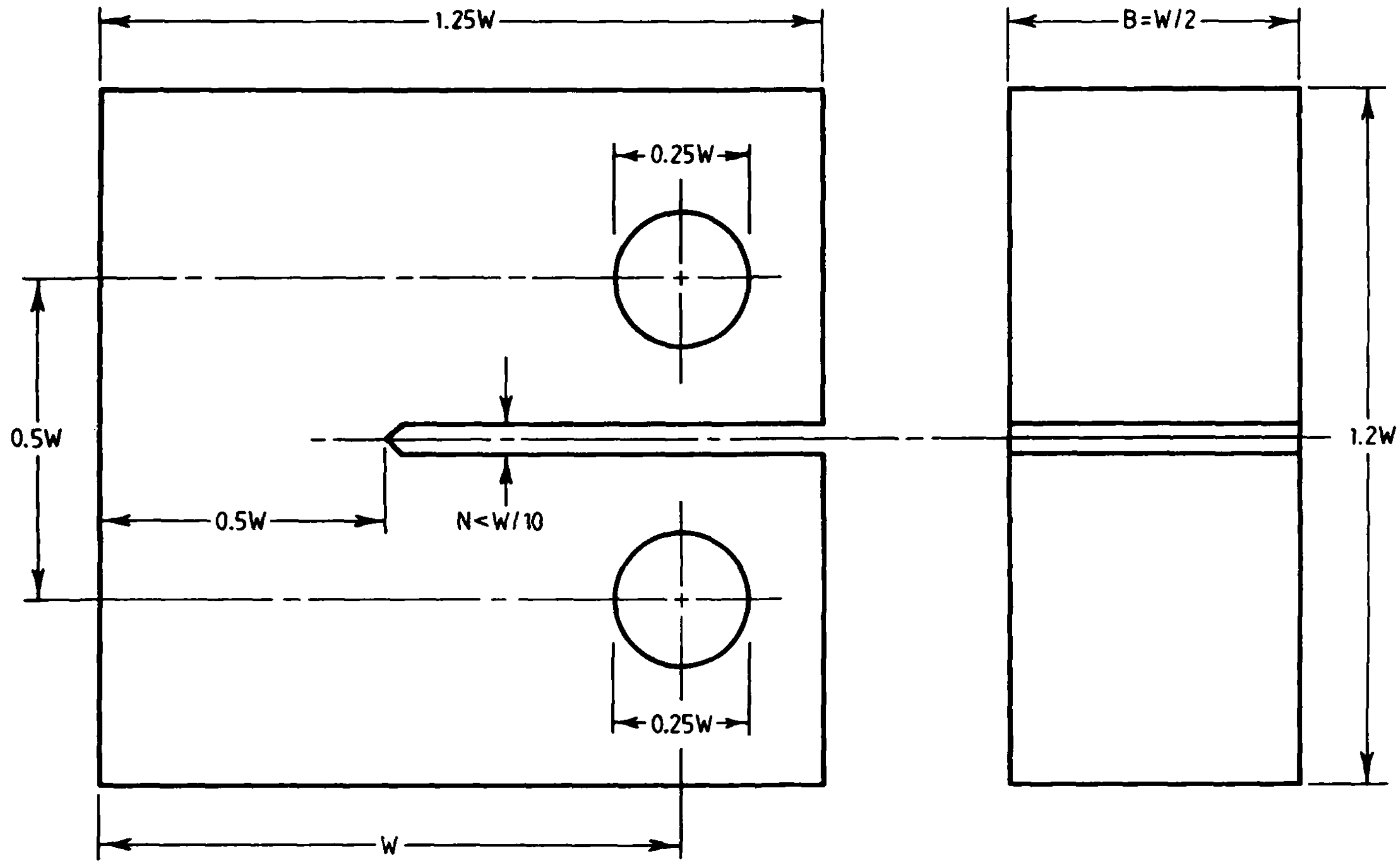


FIG. 1 ASTM COMPACT TENSION SPECIMEN

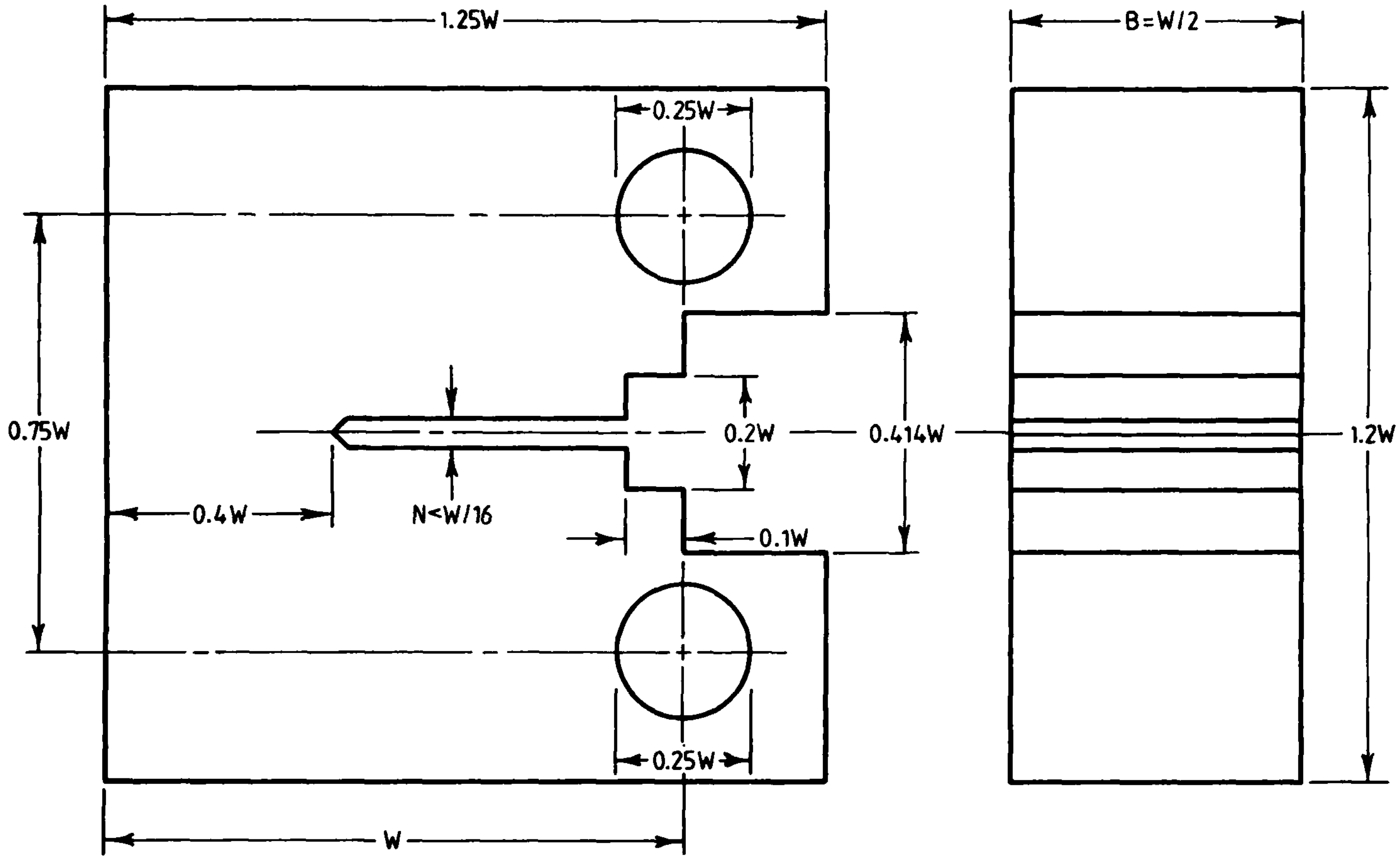


FIG. 2 ASTM J INTEGRAL SPECIMEN

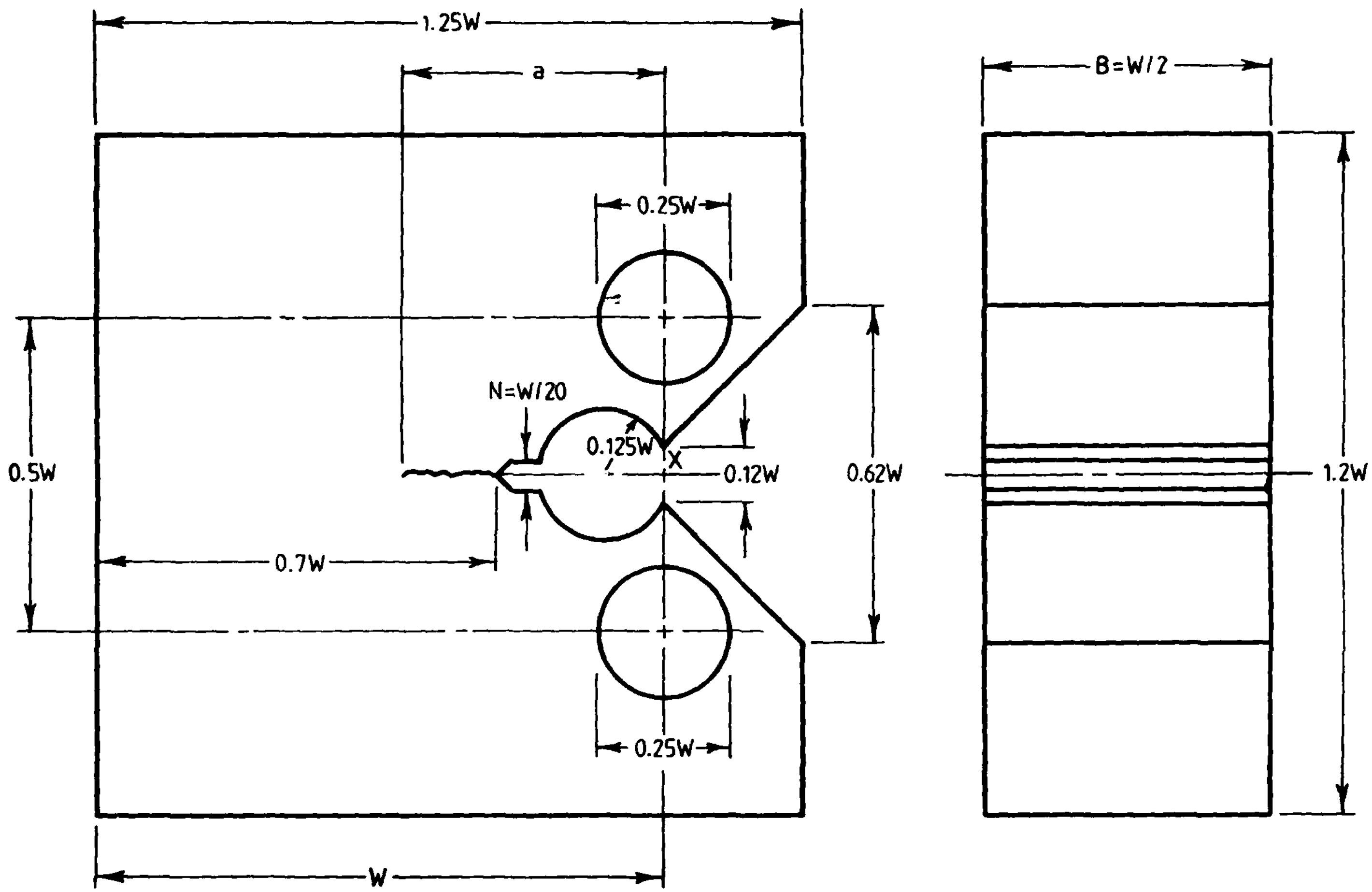


FIG. 3 MRL COMPACT SPECIMEN A

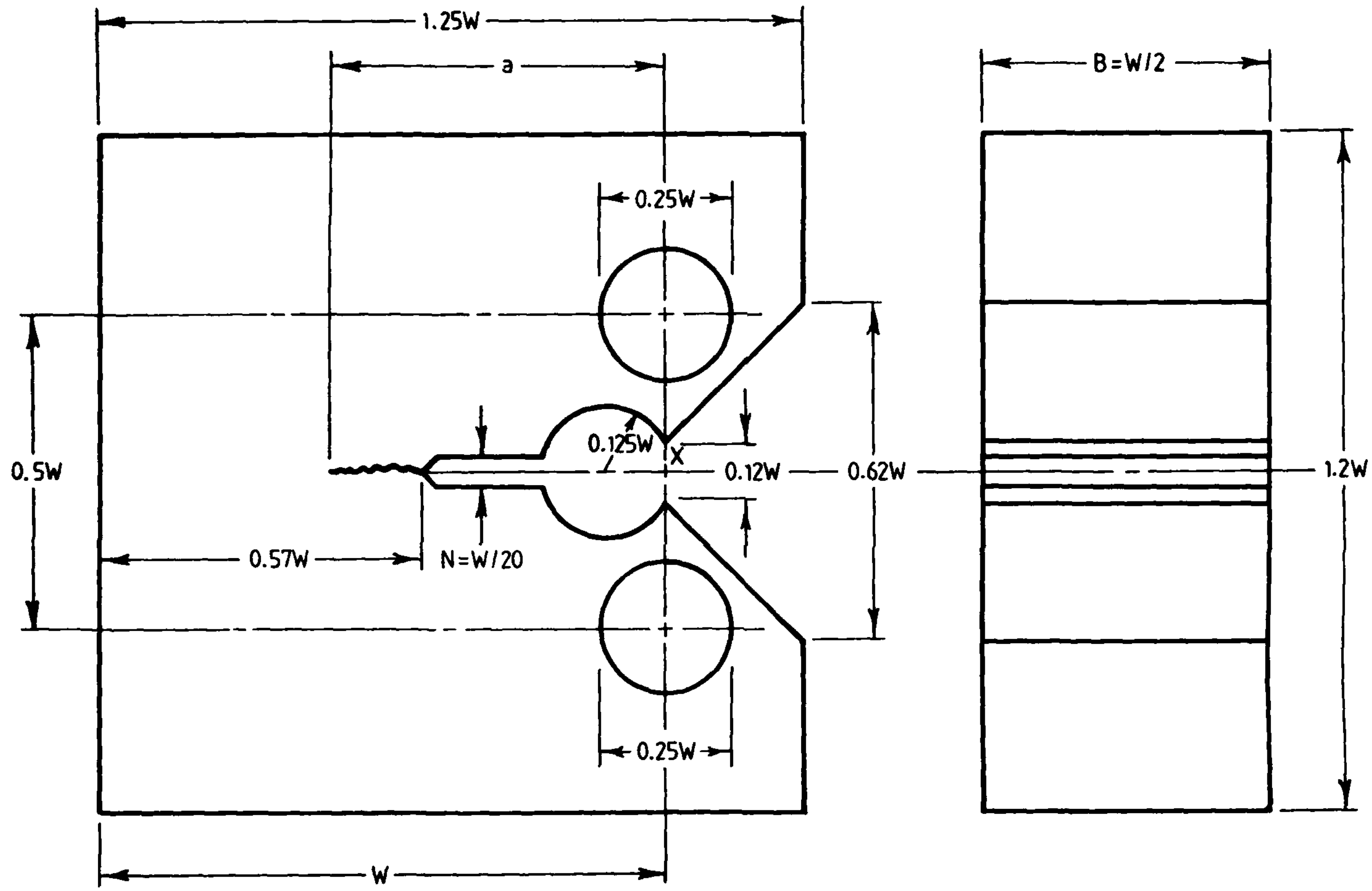


FIG. 4  MRL COMPACT SPECIMEN B

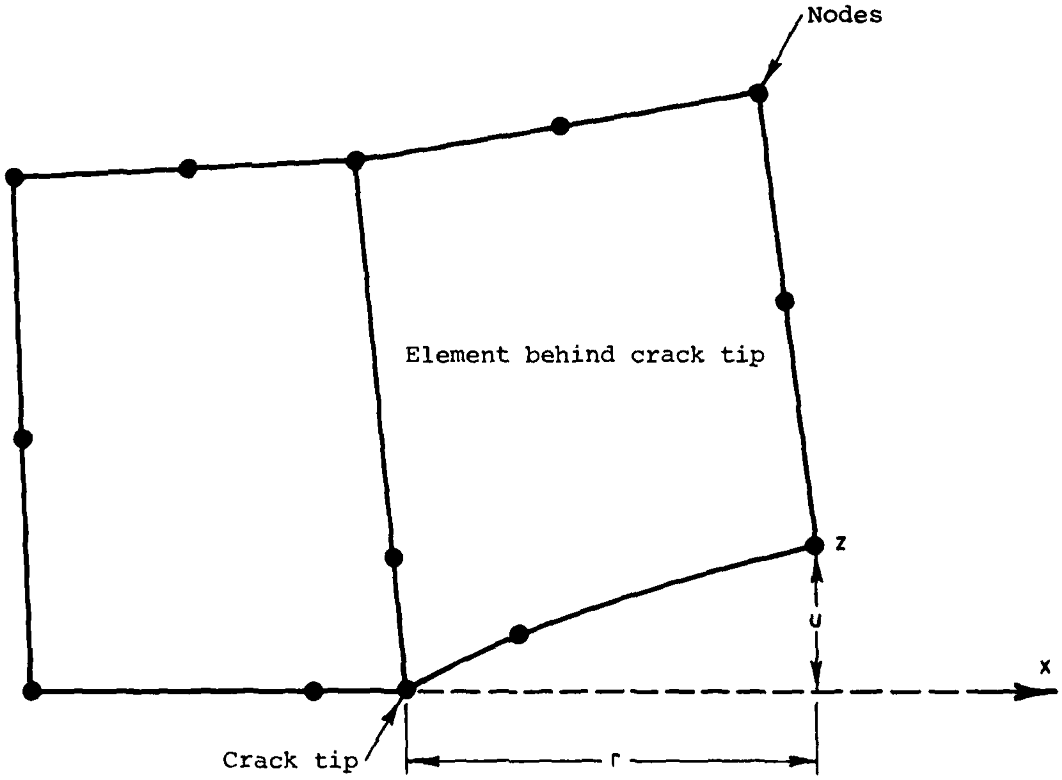


FIG. 5 GEOMETRY FOR DETERMINATION OF K
FROM DISPLACEMENT OF NODE Z

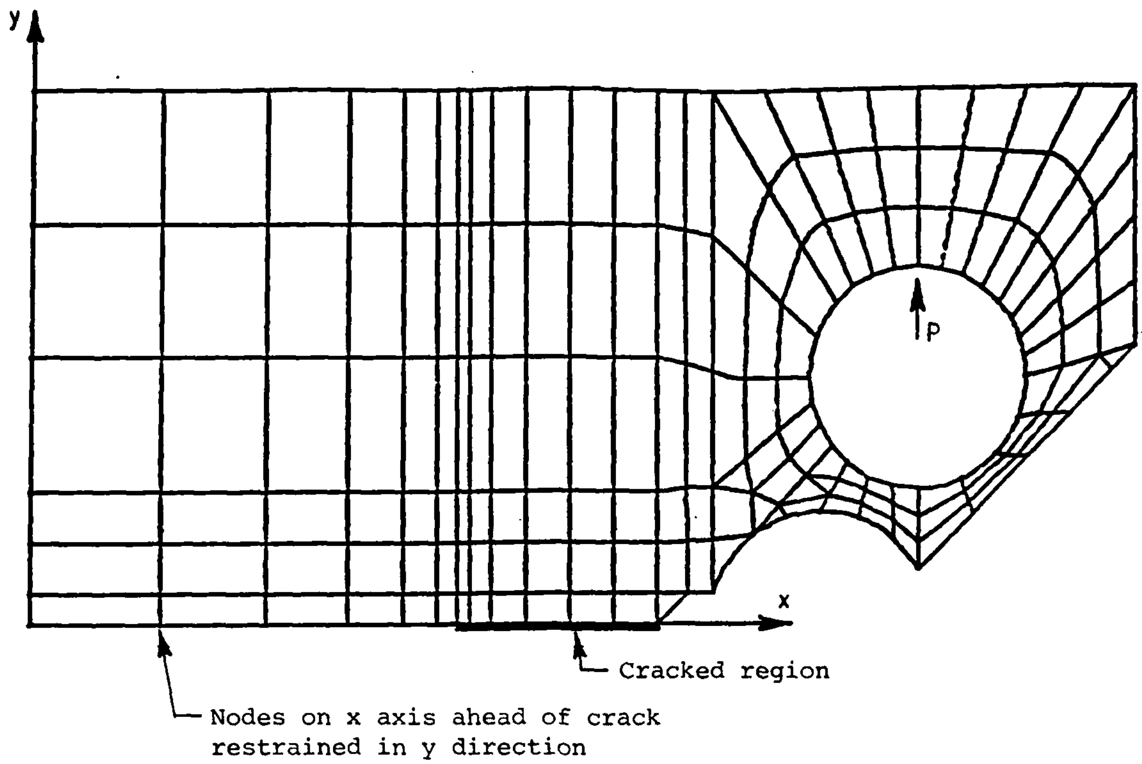


FIG.6(a) FINITE ELEMENT MESH FOR MRL COMPACT SPECIMEN 'A' WITH POINT LOADING

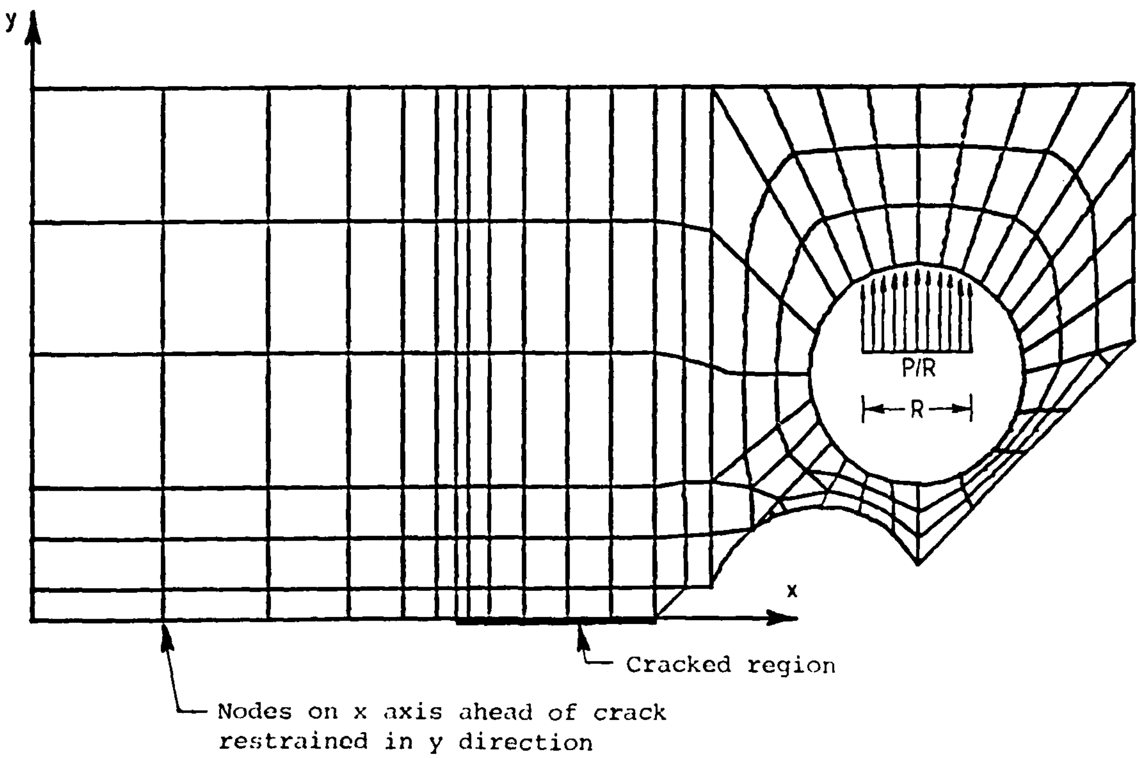


FIG.6(b) FINITE ELEMENT MESH FOR MRL COMPACT SPECIMEN 'A' WITH DISTRIBUTED LOADING

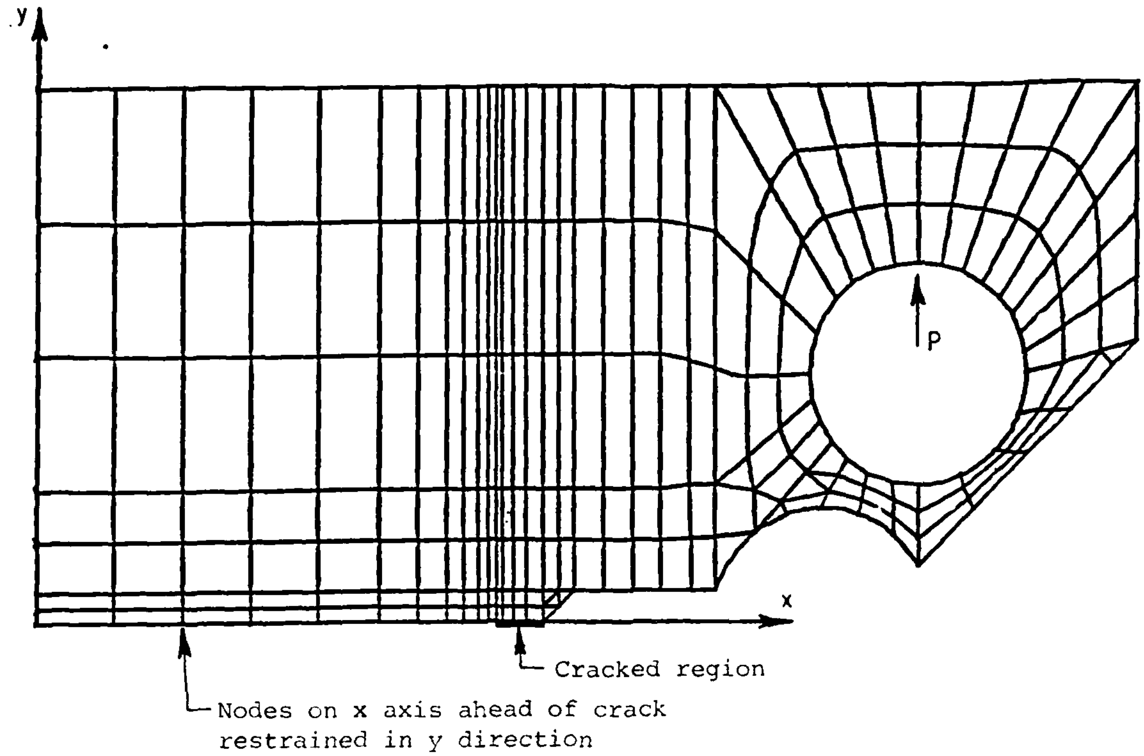


FIG.7(a) FINITE ELEMENT MESH FOR MRL COMPACT SPECIMEN 'B' WITH POINT LOADING

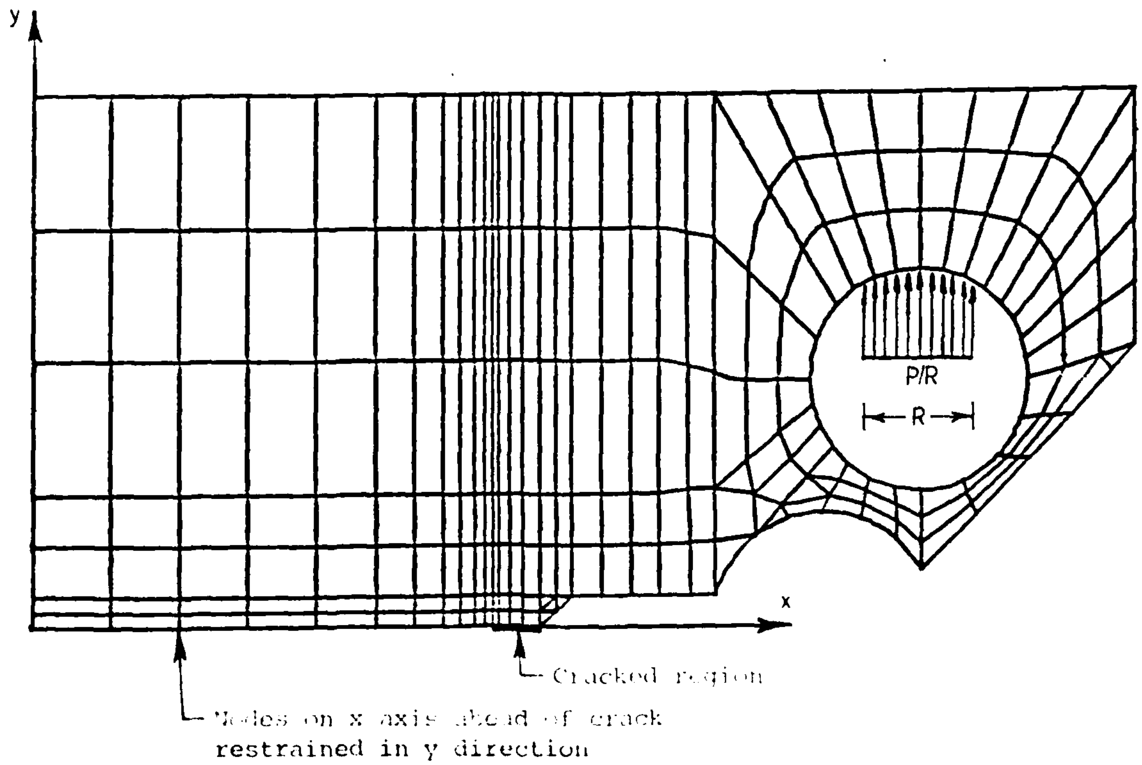


FIG.7(b) FINITE ELEMENT MESH FOR MRL COMPACT SPECIMEN 'B' WITH DISTRIBUTED LOADING

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16. Abstract

At Materials Research Laboratories (MRL) Melbourne, a compact specimen design has been developed which is suitable for both plane-strain fracture toughness and $J_{IC}$ testing. Compliance and stress intensity factor calibrations are given for the new design of specimen using finite element analyses and the results are compared with those for the ASTM compact specimen.

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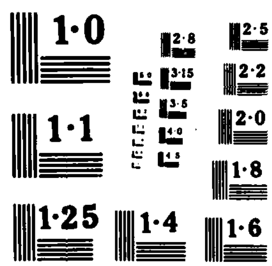
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ERRATA

On page 3 the equation,

$$\tilde{K} = \frac{K B \sqrt{W}}{P} \qquad (3)$$

is incorrect. It should be,

$$\tilde{K} = \frac{0.2258 \, K B \sqrt{W}}{P} \qquad (3)$$

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